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TRANSLATION

THEORY OF SUPERCONDUCTIVITY

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THEORY OF SUPERCONDUCTIVITY

by

N. N. Bogolyubov

The phenomenon of superconductivity was discovered as far back as 1911 by the Dutch scientist Kammerlingh Onnes. This scientist was the first to succeed in converting gaseous helium into a liquid (1908) and to obtain a temperature that was only a few degrees above absolute zero (0°K—zero degrees on the Kelvin scale), i. e., minus 273.16° centigrade. In studying the resistance of mercury in the range of temperature reached, Kammerlingh-Onnes hit onto the remarkable phenomenon, mercury ceased to show any resistance to an electric current passing through it. At the temperature of 4.12 on the absolute scale it passed into the superconductive state.

Later it turned out that not only mercury can be superconductive. At the present time there are known 23 pure metals which possess the property of superconductivity (among them such metals as tin, lead, aluminum, zinc, and others. Besides, a great number of compounds and alloys at low temperatures also become superconductors.

The remarkable property of superconductivity was demonstrated with special lucidity in an experiment with a leaden superconductive ring which was not connected up with any source of electrical energy. An electric current excited in it can circulate in it for hours, practically as long as it is possible to hold the low temperature of the experiment.

In 1933 the German scientist W. Meissner discovered the not less curious magnetic properties of the superconductors. In these experiments the superconductor was placed in a magnetic field and cooled until it passed into the superconductive state. The magnetic field when this happened was pushed out of the volume of the superconductor and concentrated in a very narrow (of the order of 10^{-5} cm) surface layer. Thus the magnetic field cannot penetrate the interior of a substance which is in the superconductive state. This phenomenon received the name of the Meissner effect.

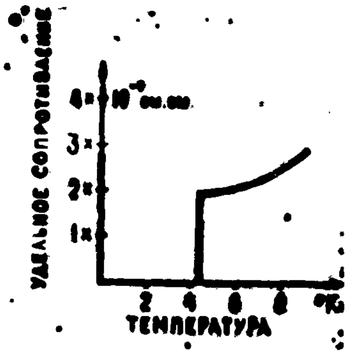
The zero resistance to an electric current and the magnetic properties of the superconductors in their nature proved to be fundamental facts, with the aid of which, without resorting to extraneous hypotheses, the British scientists F. London and G. London were able to explain the nature of almost all existing experimental material.

However, for a long time one was not able to give an explanation to these phenomena notwithstanding the very considerable interest manifested by the scientists of the whole world in superconductivity during the course of almost half a century. Only quite recently the numerous attempts in this direction were crowned with success.

Academician N. N. Bogolyubov

But before taking up the story of the new accomplishments in clearing up superconductivity it is in place to call attention to still one more remarkable phenomenon also observed at very low temperatures. We have in mind the superfluidity of liquid helium. Although this phenomenon was discovered considerably later than superconductivity (in the year 1938 by the academician P. L. Kapitsa) it got full explanation almost ten years earlier.

What kind of a phenomenon is this superfluidity which has such affinity with superconductivity? It is known that at the absolute temperature of 4.2° and down (right down to absolute zero) helium finds itself in the liquid state (if the pressure is less than 25 atmospheres), but when the temperature 2.19° K is reached helium passes into a special superfluid state, with no more viscosity, such as is characteristic of any ordinary liquid or gas. In this state the helium acquires the capacity to flow through the thinnest capillaries quite freely, and for its movement there is not required a difference of pressures, just as the current flows through the superconductive ring without a difference in potential.



With the lowering of the temperature the resistance of mercury diminishes gradually, but at the temperature of 4.2°K the curve drops sharply--electrical resistance becomes zero--it passes into the superconductive state. Key: left, specific resistance; below, temperature.

As it now has now turned out the physical nature of superconductivity and superfluidity are almost one and the same thing; between these phenomena there exists a profound physical and mathematical analogy.

To characterize in a few words the latest accomplishments in explaining superconductivity one should say that superconductivity is superfluidity of the electrons in the metal.

In explaining superfluidity an important role was played by the theory of Academician L. D. Landau. Based on a series of shrewd premises about the microscopic nature of this phenomenon it made it possible to explain some characteristic traits of superfluidity. In 1947 the author of these lines succeeded in developing a consistent microscopic theory of superfluidity and deriving special mathematical procedures which now lie at the basis of a new method enabling one to solve completely the problem of superconductivity.

With this theory there was explained the following picture of the movement of a superfluid liquid: in opposition to an ordinary liquid or gas in which individual particles are shifted along chaotically the superfluid liquid manifests a high degree of orderlyness. This is brought about by a powerful interaction among the separate particles of the superfluid liquid, and this proves to be very strong for particles the velocities of which are directed in opposition to each other. It was precisely the correct calculation of this interaction also that caused the basic difficulty in creating a theory of superfluidity.

In the superfluid liquid by virtue of the powerful interaction of the pairs of particles with equal and opposed directional velocities there is formed a special "condensate." The particles that find themselves in it cannot give out their energy in little portions. As a whole the superfluid liquid finds itself deprived of viscosity. The "condensate" can be formed only a comparatively low temperatures, and therefore the phenomenon of superfluidity is observed only close to absolute zero.

Let us pass over now to the superconductivity. Let us recall briefly in general lines the mechanism of ordinary conductivity of metals.

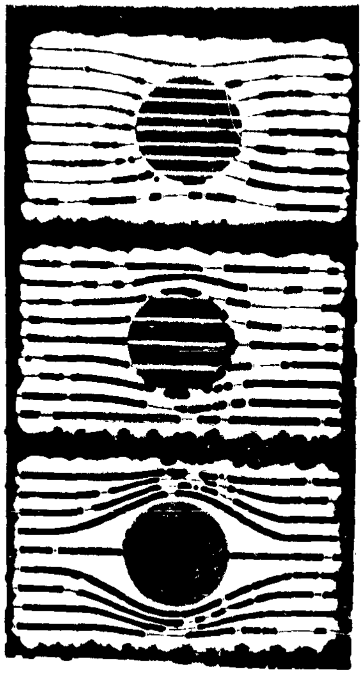
In metals the atoms are not arranged in disorderly fashion but by regular rows. They thus form the so-called crystalline lattice. The electrical current represents the flow of the electrons. In passing through metal the electrons collide with atoms of the crystalline lattice and thereby bring about their oscillations. Meanwhile the electrons give off their energy to the atoms and are retarded. It is natural that the flow of electrons by virtue of this experience a definite resistance.

Into this picture of the conductivity of metals, which we inherited from classic physics, modern quantum physics brought its changes. According to the principles the ideal crystalline lattice at the temperature of absolute zero does not offer resistance to an electrical current, but at any temperature, even though of small degree, resistance occurs as a result of the collision of the electrons with the quanta of heat oscillations of the lattice, the phonons. One should mention that the notion of the phonon, which plays now such an important role in the whole theory of metals, was first introduced to science by the Soviet scientist and academician I. E. Tamm.

Thus from the point of view of modern concepts the interaction of electrons with the atoms of the crystalline lattice is more correctly presented as the interaction of electrons and phonons. The character of this interaction is such that the electrons can absorb and emit phonons. In the latter case the electron loses its energy.

We dwelt here in a little more detail on a description of the pattern of ordinary conductivity of metals. We did this also because it is precisely the interaction of the electrons with the phonons (the creation under ordinary circumstances of the resistance to the movement of the electrons in metal) which proves to be, as it now has turned out, the basic reason for the formation of superconductivity.

This important physical idea about the existence of the role of the electron-phonon interaction was first expressed by the British scientist H. Froehlich in 1950. Up to that time it was considered that the weak electron-phonon reaction should be disregarded and one should take into account only the powerful direct electrostatic interaction of the electrons among themselves. Froehlich derived the basic equation of the problem, but in view of the exclusively mathematical complexity was not able to make the solution, although he expressed a number of correct hypotheses about the nature of the mathematical difficulties.



Pushing aside of magnetic force lines by a superconductor sphere in its passing into the superconductive state (Meissner effect). Above are shown the magnetic-force lines when the sphere has not yet passed into the superconductive state; in the center is shown the same sphere at a lower temperature; the bottom drawing indicates the arrangement of the magnetic-force lines around a sphere which has passed into the superconductive state. The lines are completely pushed out of the volume of the sphere.

Starting with his idea of the electron-phonon interaction he succeeded in predicting the so-called isotopic effect. He comes to the conclusion that the temperature of the transition into the superconductive state in a definite way depends on the mass of the atoms which form the crystalline lattice of the metal, namely, this temperature is inversely proportional to the square root of the atomic weight of the isotope. This prediction in 1950 was brilliantly confirmed experimentally. It became clear that Froehlich's notion basically expresses correctly the physical nature of the phenomenon.

However, up to this time no complete solution has been given to Froehlich's equations; doubts remained as to whether really proceeding from these equations one could explain the phenomenon of superconductivity. Does one not need to bring in additional physical ideas? Froehlich's notions were attractive, but they did not have, strictly speaking, convincing force. They remained on the level of hypotheses, awaiting to be verified. Such a verification could be provided by an exact solution of Froehlich's equations. Many scientists in various countries worked on this problem.

An important physical idea about the reason of the difficulties in the solution of Froehlich's equation was expressed by the Australian scientists M. R. Shafroth, S. T. Butler, and J. M. Blatt. They introduced the idea about the essential role of special paired correlations between the electrons and the electron-phonon system.

Such ideas, but supported already by mathematical computation, were developed in a recent work by American scientists, J. Bardeen, L. N. Cooper, and J. R. Schrieffer. They dealt with a somewhat simplified model, in which there figured the interaction of electrons somewhat like gravity. By introducing the supplementary hypothesis that the electrons are grouped in pairs these researchers obtained a series of formulas, which correctly describe the bond between the main values which characterize the state of superconductivity. Notwithstanding the fact that in the work of Bardeen, Cooper, and Schrieffer there is a whole series of insufficiently founded physical and mathematical propositions, it must be considered as an important contribution to the theory, considering the extreme complexity of this problem.

In working on the theory of superconductivity we were so successful in developing our method applied to the formation of a theory on superfluidity, that it enabled one fully and strictly to solve the problem, not only as initially proposed by Froehlich, but also with its supplemental complications, produced, for example, by taking into systematic account the electrostatic repulsion of the electrons. This new method in the development of which an important part was taken by my collaborators D. N. Zubarev, V. V. Tolmachev, S. V. Tyablikov, Yu. A. Tserkovnikov, and D. V. Shirkov is based on the development of the ideas of our work in accordance with the microscopic theory of superfluidity published ten years ago.

In normal metal the electrons move in disorderly fashion. If a difference of potential is applied to the metal this movement becomes somewhat more orderly. However, the electrons will still collide with atoms of the crystalline lattice of the metal. When this happens the electrons give up their energy, which goes into the excitation of oscillations of the of the separate atoms (right upper atom on the left drawing). From the point of view of the quantum theory the electron here emitted a phonon. The movement of the electrons in the metal when it is in the superconductive state acquires a high degree of orderliness. The electrons form a special powerfully bound collective, which cannot now give out its energy in small portions. The flow of the electrons meets no resistance on the part of the lattice; the electrical resistance is brough to zero (right-hand drawing).

As a result of the researches conducted it turned out that the phenomena of superconductivity and superfluidity are physically and mathematically allied. The establishment of this fact is very essential because up to the present time in physics circles the opinion prevailed that altogether it was hardly possible to have an affinity between the behaviors of a system consisting of atoms of helium and a system consisting of electrons. The matter is that the static properties of these particles, which also determine the behavior of the systems made up of them, are quite different.

One can get a general picture of the behavior of the electrons in the superconductive state in the following fashion. The free electrons in this state form a bound collective, in its properties similar to that which in the theory of superfluidity is called "condensate." In order to tear an electron out of this collective it is necessary to do work the magnitude of which is of the same order as the heat energy corresponding to the temperature of transition from the superconductive into the normal state. Due to such a bond the movement of the collective as a whole proves to be stable; the electric current in the metal does not meet with resistance.

The electrostatic repulsion of the electrons, of course, operates against the formation of such a "condensate." However, this repulsion, as we now know, operates much more weakly than was assumed in the Bardeen-Cooper-Schrieffer theory.

Besides, the new method made it possible to compute the oscillations of the collective of electrons and establish the existence of a special kind of excitation—electronic waves, the energy of which is inversely proportional to their length, and directly proportional to the maximum velocity of the electrons.

The formulation of the theory of superconductivity opens up broad prospects for the solution of many practical important problems connected with the use of superconductors in modern technology. Although these possibilities (for example, the transmission of electrical energy over a long distance) promise great economic effect up to the present time the application of superconductors has only been sporadic. This is explained by the fact that superconductors exist at very low temperatures--not above minus 250° centigrade.

One can think that the theory of superconductivity will be able to solve in principle the problem of the possibility of creating a superconductor at room temperature.

In connection with this subject one should express the hope that our mathematical method which made it possible to create both the theory of superfluidity and the theory of superconductivity will enjoy broad application in other fields of statistic physics.

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